

Repairing Delaminations with Low Viscosity Epoxy Resins

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1. SUMMARY

Although resin injection is the procedure most often specified for repairing delaminations, field experience as well as numerous experimental investigations have shown it to be unreliable and in many cases ineffective. This paper identifies some of the reasons for this and then goes on to describe the successful development of an epoxy resin specially formulated for delamination repair. The ability of this resin to fully restore the out-of-plane properties of delaminated carbon/epoxy laminates is demonstrated and some of the more practical aspects of repairing delaminations both on and off aircraft are discussed.

2. INTRODUCTION

The Achilles' heel of most laminated organic matrix composite materials currently utilized in advanced fighter aircraft and helicopters is their poor interlaminar properties. Both during assembly and in-service this weakness can lead to the formation of delaminations from a number of different causes including hole drilling, fastener installation, pry damage, impact damage, free edge stresses and lightning strikes. While considerable research and development activity has been directed towards characterizing the interlaminar fracture and fatigue properties of these materials and to assessing the structural significance of delaminations, much less effort has gone into developing effective repair procedures. Most of the repair options that have been considered involve one of the following:

- (i) removal of the delaminated material and installation of a patch;
- (ii) stabilization of the delaminated plies with mechanical fasteners; or
- (iii) injection of an adhesive into the delaminations.

The suitability of each of these procedures depends on the loading conditions, the thickness of the part and the nature of the material. For example, impact damage of lightweight honeycomb sandwich structure, will normally require the removal of the delaminated skin material to gain access to the damaged core. On the other hand, for laminates thicker than 5 mm, bonded scarf patches become excessively large and the use of bolted patches may be limited by weight restrictions and airflow perturbation considerations. Under these circumstances, options (ii) and (iii) are clearly preferable. For monolithic carbon/epoxy structure containing fastener holes it has been demonstrated that

by using blind fasteners to "clamp-up" impact damage induced delaminations it is possible to fully restore the design ultimate compression strength [1]. However, in regions of high interlaminar shear stress or in bonded structures which experience design strains in excess of 4000 micro-strain it is unlikely that this approach would be satisfactory. Under these conditions, resin injection would appear to be the most promising method for repairing delaminations in as far as it produces no significant stress concentration, results in a negligible increase in weight and has the potential to fully restore all of the interlaminar properties. Unfortunately, most reported attempts to develop and qualify resin injection repairs have been unsuccessful [1-3]. These findings are supported by our own experience with resin injection repairs of delaminations on the CF-18, which is that the qualified adhesive and procedure specified in the structural repair manual seldom work satisfactorily.

This paper reviews the results of a research program aimed at improving our ability to repair delaminations in the carbon/epoxy structure of the CF-18 aircraft. The origins and nature of these delaminations is discussed and tests carried out to quantify and model the flow of resin into some typical delaminations are described. The rheological, thermal and mechanical properties of a specially formulated epoxy resin are characterized and its ability to completely infiltrate and rebond delaminations is evaluated. Tests to determine to what extent it is possible to restore the compression strength, damage tolerance and the ability of the laminate to support high interlaminar shear stresses are described. Finally, some specific delamination repair procedures for use both on-aircraft and in an autoclave are suggested and the influence of contaminants entering the delaminations prior to repair investigated. A more detailed description of some of this work can be found in references 4-7.

3. CF-18 SERVICE EXPERIENCE

Generally speaking, the carbon/epoxy composite structure on the CF-18 has proven to be relatively damage resistant. Most of the damage requiring repair has been caused by mishandling or by foreign object damage either in flight or on take-off and landing and has been limited by and large to the lightweight honeycomb sandwich structure found on the flight control surfaces and numerous doors and access covers. See Figure 1. The monolithic carbon/epoxy structure, which is mostly between 5 and 15 mm in thickness and limited to the wing skins and vertical stabilizer, has a higher impact energy threshold and is

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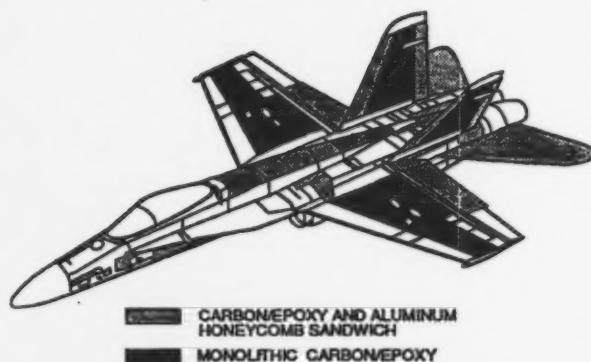


Figure 1. Usage of carbon/epoxy on the CF-18.

also less likely to show visible signs of damage. Since no routine non-destructive examinations are carried out, the existence and distribution of delaminations is largely unknown. However, some of the trailing edge wing panels were partially inspected ultrasonically in 1989 following the discovery of a manufacturing related problem associated with the mechanical attachment of the skins to the underlying substructure. An unexpected sensitivity to fit-up tolerances at rib/spar joints, as shown in Figure 2, had produced delaminations adjacent to fastener holes in some trailing edge panels. Out of approximately 30 fastener

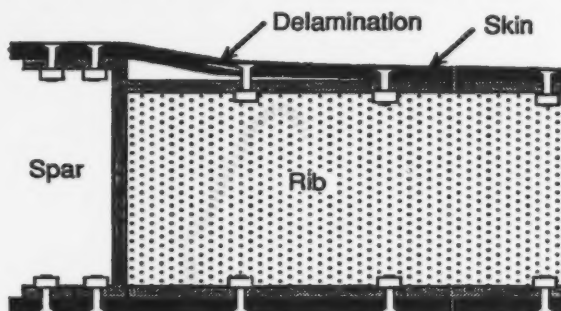


Figure 2. Localized bending and delamination caused by poor fit-up.

holes that were inspected on each trailing edge panel on 15 different aircraft an average of one delamination per aircraft was found. In most instances the delaminations were less than 25 mm in diameter, although in some cases the manual inspections indicated delaminated areas as large as 50 x 80mm. Based on recent C-scanning of some of the delaminations, it has been concluded that inspections with hand held transducers tend to over-estimate the size and degree of connectivity of the delaminations. In addition to the type of delaminations described above it is also likely that wing-skin delaminations resulting from impact damage could occur from time to time, although as mentioned before this has not been a problem to date. It was therefore the goal of this program to develop resin injection repairs for both fit-up and impact induced delaminations.

4. RESIN INFILTRATION TESTS

Figure 3 shows the geometry used to model the flow of resin into a delamination. The resin enters the delamination under pressure P_1 through a hole of radius R_1 and is assumed to flow radially outwards within the delamination cavity of opening h . For a resin

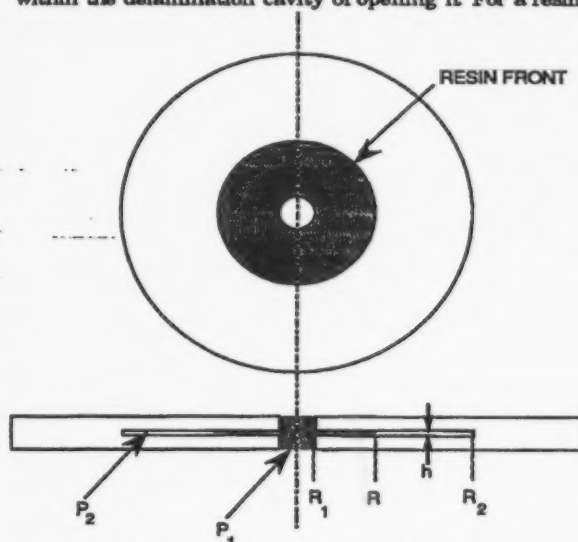


Figure 3. Resin flow model geometry.

of viscosity η the time taken to reach a radius R is given by [4]:

$$t = \frac{3\eta [R^2 (2 \ln(R/R_1) - 1) + R_1^2]}{(P_1 - P_2) h^2} \quad (1)$$

where P_2 is the pressure ahead of the resin front. In order to verify the applicability of this model to real delaminations, and to determine typical values for h , a series of infiltration tests were carried out. The holed plate shear (HPS) test specimen shown in Figure 4 reproduces the fastener hole and shear loading of the fit-up problem described above while maintaining the concentric geometry of the resin flow model.

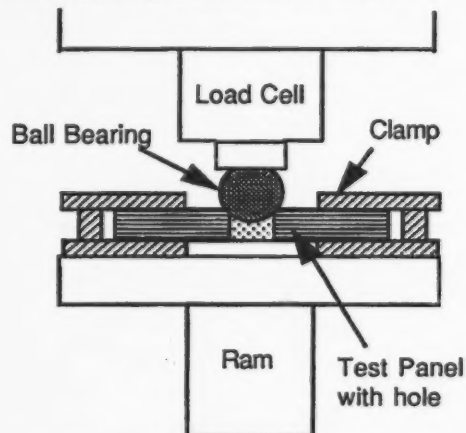


Figure 4. Holed plate shear test loading arrangement.

Delaminations are created by applying a load to the fastener hole while supporting the specimen on a ring of the desired diameter. Initial tests were carried out on the same material and stacking sequence as the CF-18 trailing edge panels (48 plies of Hercules' AS4/3501-6 carbon/epoxy comprising 8% 0s, 84% ± 45 s and 8% 90s). In later tests the thickness was varied but the ply orientation percentages were kept the same.

Resin infiltration was carried out in an ultrasonic C-scan tank so that the resin front position could be determined as a function of time. A low viscosity epoxy resin without curing agent was forced into the fastener hole under pressure after pre-evacuating the delaminations. Details as to how this was accomplished are given in Reference 4. Figure 5 shows one set of C-scan images recorded during the infiltration of a 48 ply specimen containing 76 mm diameter delaminations.

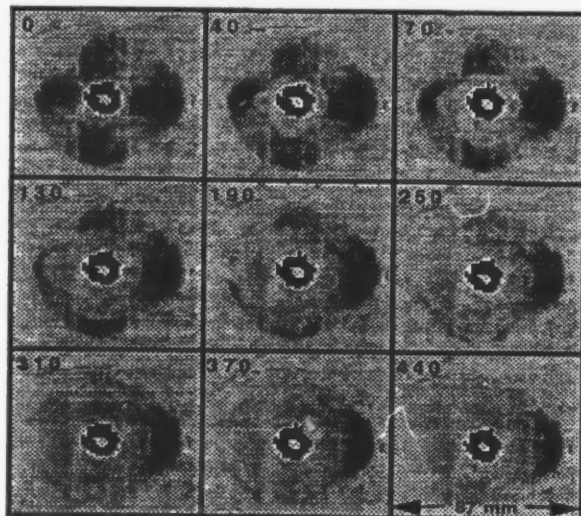


Figure 5. A series of C-scan images showing resin infiltration as a function of time (minutes).

The resin front position in each of the 4 quadrants of the delaminated area was measured from each image and plotted as a function of time. Equation 1 was then least squares fitted to each data set using h as the fitting parameter. Figure 6 shows the data fits corresponding to the images shown in Figure 5. In most cases the

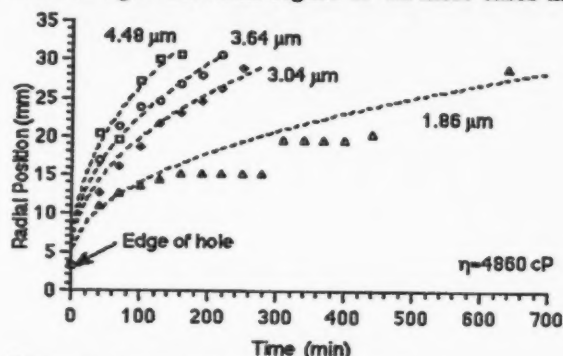


Figure 6. Resin front position versus time.

agreement with the model was quite good, with values of h ranging from 1 to 10 μm . The fitted values of h will be referred to as h_{eff} since they represent the effective delamination opening for resin flow and appear to be somewhat lower than the actual openings observed microscopically on polished cross sections (see figure 16 for example). As might be anticipated, there was considerable scatter in the h_{eff} values from quadrant to quadrant and from one specimen to another. Nevertheless, the results showed a strong dependence of h_{eff} on both delamination size and laminate thickness as shown in Figures 7 and 8. While it is evident that the

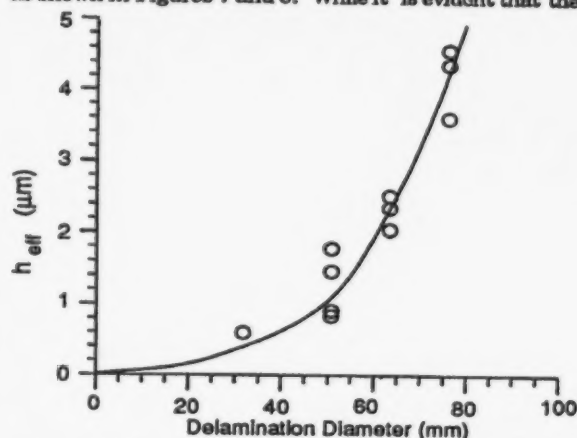


Figure 7. Effect of delamination size on delamination opening.

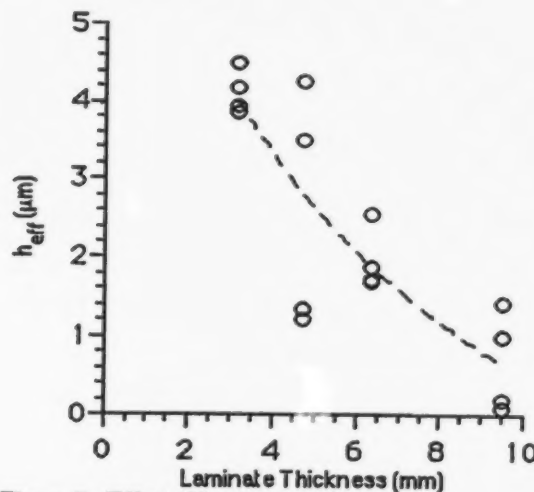


Figure 7. Effect of laminate thickness on delamination opening.

higher h_{eff} values correspond to greater thru-thickness compliances, no increase in h_{eff} was observed as the injection pressure was raised. It is hypothesized that the delaminations open momentarily following the initiation of delamination growth and that fracture debris limits the extent to which they subsequently close up. The thinner HPS specimens and those supported on the larger diameter clamps are less restrained from opening and therefore end up with larger values of h_{eff} .

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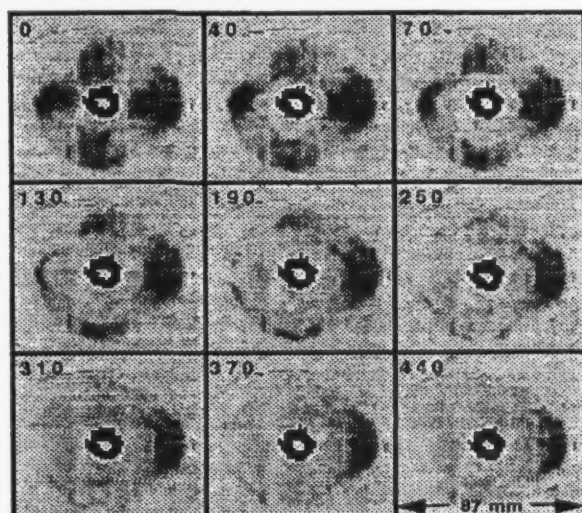


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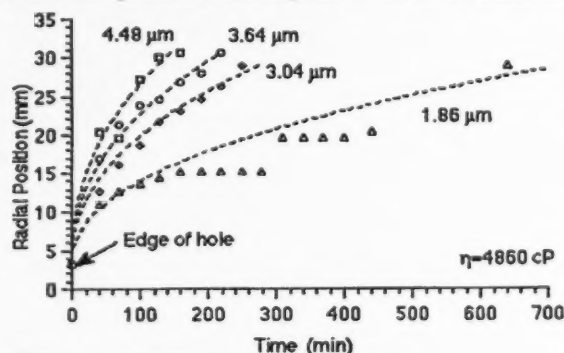


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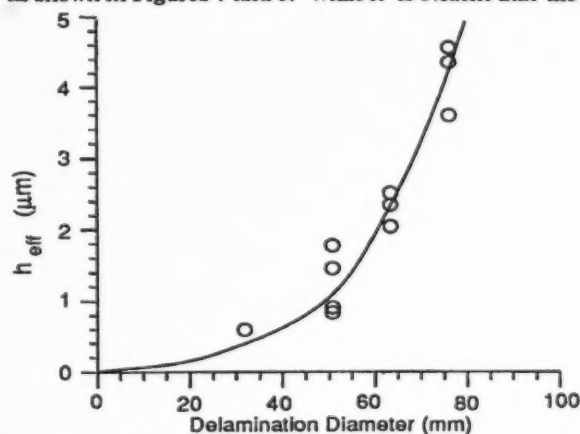


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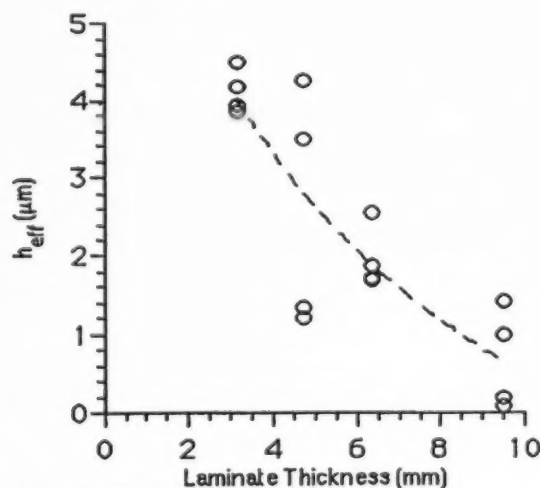


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From the flow model and the measured values of h_{eff} it is possible to predict the amount of resin flow required to successfully repair some typical delaminations. First, however, it is necessary to recognize that the resin viscosity is a function of both time and temperature. By modifying Equation 1, the total flow potential of the resin from the time of mixing to the time of cure can be compared with the flow requirement to completely fill an area of radius R_2 :

$$\int_{t_0}^{t_{cure}} \frac{1}{\eta} dt \geq \frac{3[R_2^2 (2 \ln(R_2/R_1) - 1) + R_1^2]}{(P_1 - P_2) h_{eff}^2} \quad (2)$$

Table 1 gives the value of the quantity on the right hand side of Equation 2 for some representative delamination

Table 1. Resin flow requirements for some typical repair conditions. Laminate thickness = 6mm.

Delamination Size		Resin Flow Requirement (Pa^{-1})	
Diameter (mm)	h_{eff} (μm)	350 kPa on-aircraft repair	700 kPa autoclave repair with vacuum
30	0.4	52680	26340
50	1.4	14400	7200
75	3.9	4740	2370

sizes and injection parameters. These data reveal that small delaminations provide greater flow resistance to resin infiltration than larger delaminations and indicate that a viable delamination repair resin should have a flow potential of the order of 50,000 Pa^{-1} . In comparison, the epoxy adhesive currently specified for delamination repair on the F-18 was found to have a flow potential of only 800 Pa^{-1} and because of the short pot life not all of this is realized in practice. Although other commercially available epoxy adhesives having superior flow properties were identified none of these approached the desired 50,000 Pa^{-1} . Consequently, the development of a resin system designed specifically for repairing delaminations was undertaken in house.

5. RESIN DEVELOPMENT

5.1 Adhesive Formulation

In addition to the aforementioned flow requirement, an adhesive for repairing delaminations must also possess a number of other properties. These include the ability to effectively rebond the delaminated surfaces together and an adequate resistance to the moisture and temperature regimes encountered by the component being repaired as well as a cure temperature that is compatible with on-aircraft repair. Thus, while viscosity is clearly an important consideration it should not be the over-riding factor in formulating a resin system. For example, a low viscosity bi-functional epoxy was chosen rather than a lower viscosity mono-functional epoxy because of the low glass transition temperature, T_g , and poor mechanical properties resulting from the latter's inability to cross link. Likewise, very low viscosity amines were avoided as curing agents because their high volatility can cause them to "boil off" during cure, producing a porous bond

line. Latency of cure, as determined by differential scanning calorimetry, was the key parameter in selecting a curing agent. Other factors which influenced the resin formulation were surface wetting characteristics, and the ability to withstand a post-cure at 177°C, which might arise if the same component required a full autoclave repair at some later date.

The delamination repair epoxy that was ultimately developed will be referred to in this paper simply as the DREp resin. Unless otherwise stated, the cure cycle used consisted of a 0.5°C/min ramp to 140°C followed by a 2 hour hold and a cool-down cycle which lasted a minimum of 45 minutes. This gave a glass transition temperature of close to 140°C which dropped to 120°C upon saturation with moisture. Cure temperatures down to 110°C also gave satisfactory results but with lower T_g s. At higher temperatures, the T_g followed the cure temperature up to 160°C with little improvement beyond this point.

5.2 Flow Properties

Figure 9 shows the reciprocal viscosity of the DREp resin as a function of time for four different infiltration cycles. At 25°C the initial viscosity was 650 centi-Poise

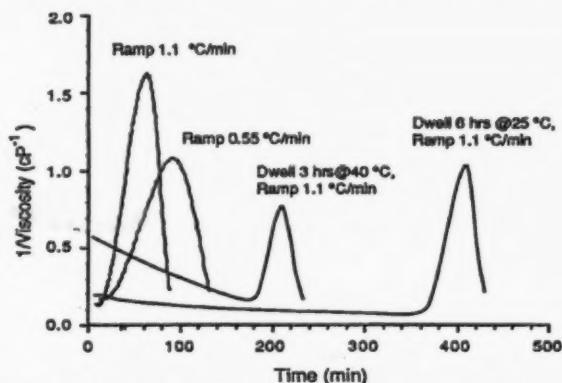


Figure 9. Plots of 1/viscosity versus time for four different infiltration/curing cycles.

(cP), increasing to 1725 cP after 6 hours. On heating freshly mixed resin at 1.1°C/min the viscosity fell to a minimum of 60 cP after 1 hour and then increased rapidly as the resin cured. The areas under the curves in Figure 9 represent the total flow potential as defined by the left hand side of Equation 2. These areas, which are plotted as a function of time in Figure 10 are relatively unaffected by the heating rate. What is important to note, however, is that for repair procedures where the resin is injected at low or ambient temperature and then cured without further application of pressure only a fraction of the total flow potential is realized. In some cases this may be as little as 50%.

5.3 Mechanical Properties

Tests were carried out to measure the interlaminar shear properties of delaminated ply interfaces rebonded with the DREp resin. Unidirectional laminates, containing 24 plies of AS4/3501-6 carbon/epoxy pre-preg and containing non-adhesive inserts on the mid-plane were fabricated and cut into 20 mm x 150 mm end notched flexure (ENF) specimens [8]. Delaminations were grown in shear from the ends of the inserts to within 20mm of the ends of the specimens. The delaminations were then opened slightly, filled with resin, clamped shut and cured for 2

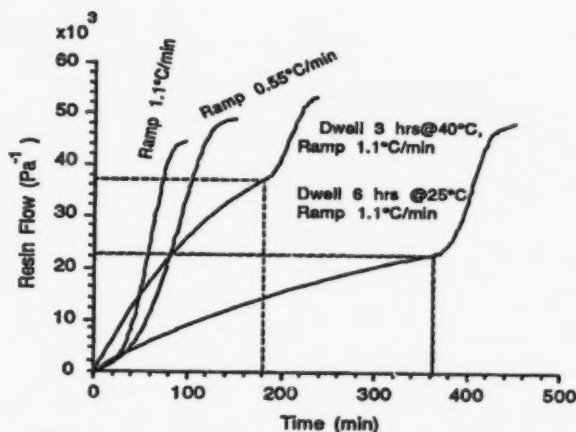


Figure 10. Flow of the DREp resin as a function of time for four different infiltration/curing cycles.

hours at 140°C. The middle 75 mm of some of the rebonded specimens were cut up into short beam shear specimens while the others were used for mode II interlaminar fracture and fatigue tests. The results of the short beam shear tests, plotted in Figures 11 and 12 indicate that the rebonded strength was close to that of

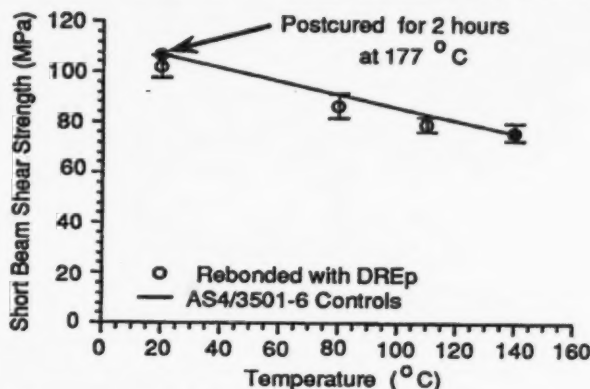


Figure 11. Short beam shear strength - dry.

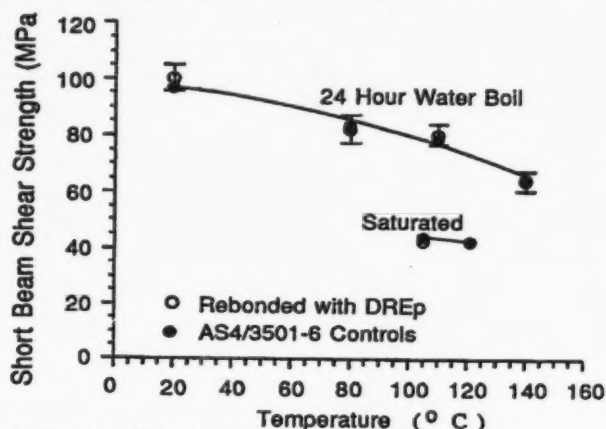


Figure 12. Short beam shear strength - wet.

the controls under all conditions tested. However, there were more mid-plane failures in the rebonded specimens particularly at elevated temperatures and after moisture conditioning. The mode II interlaminar fracture toughness, G_{IIc} as measured by the ENF test, was found to be 40 to 50% higher in the rebonded specimens than in the controls. See Table 2. While

Table 2. Mode II interlaminar fracture toughness.

Temperature (°C)	G_{IIc} (J/m ²)	Control Values (J/m ²)
20	940, 1011, 904, 927	630
100	785, 740, 758	530

some of this increase can probably be attributed to the greater toughness of the DREp resin compared to the composite matrix, part of it undoubtedly originates from the greater thickness of the interlaminar matrix layer present in the rebonded specimens and the beneficial effect that this has on G_{IIc} [9]. Figure 13 compares the interlaminar fatigue crack growth rates under shear loading of rebonded specimens with those of the controls. While no change is apparent at low values of ΔG_{II} the greater fatigue resistance at higher values is consistent with the observed improvement in G_{IIc} .

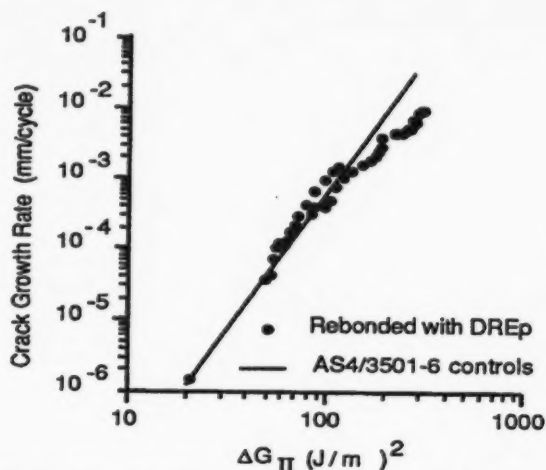


Figure 13. Interlaminar fatigue crack growth rate.

6. REPAIR OF HPS SPECIMENS

As well as providing information pertaining to resin flow, the HPS specimens proved to be suitable for evaluating resin infiltration procedures and also as a mechanical test for assessing the reparability of delaminations in regions of high interlaminar shear stress.

6.1 Resin Infiltration

Resin injection repairs to delaminated holed plate shear specimens were carried out in a two stage process as shown in Figure 14. First, the plate was placed in a transparent plastic box, the air evacuated and DREp resin injected into the fastener hole. Next the specimen

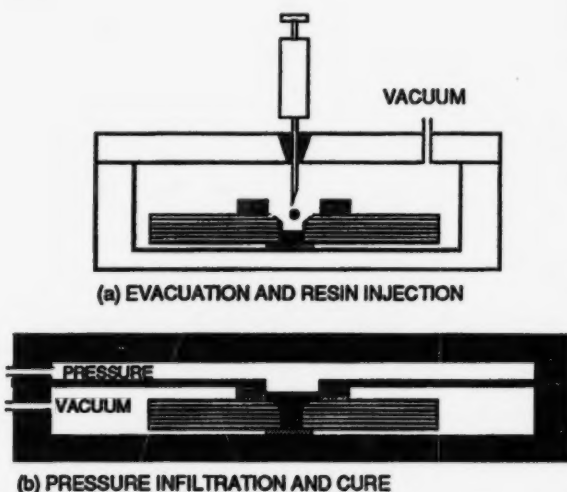


Figure 14. Repair procedure for HPS specimens.

was transferred to a steel box which was then placed between the platens of a hot press. Initially the whole of the interior of the box was pressurized (125-500 kPa) as the temperature was raised but success with this procedure was inconsistent. By pressurizing the fastener hole while the specimen was immersed in water it was discovered that there was a leakage path from the delaminations out to the specimen edge in some of the specimens. Not only did this result in a loss of vacuum but it allowed air to enter the delaminations and stop the flow of resin. This problem was eliminated by either sealing the edges of the specimen or by maintaining the vacuum throughout the cure cycle using an arrangement such as that shown in Figure 14b. When this latter procedure was adopted, resin wetted areas could often be observed on the edges of the specimens following repair. A metallographic examination of these areas revealed that the resin had leaked out via matrix cracks running transversely through the six 45° plies located at the mid-plane of the laminate.

The extent of resin infiltration was determined by ultrasonic inspection and by metallographic techniques. Figure 15 shows amplitude C-scan images of a well repaired (a) and a poorly repaired (b) HPS specimen taken before and after repair. The success of the DREp resin in filling all of the crevices and surface features on the fracture surface as well as the presence or absence of any bondline porosity was ascertained by sectioning some of the repaired plates, sanding and polishing the cut edges and examining them at high magnification with an optical microscope. In general, any plates which appeared from the ultrasonic C-scan to have been successfully repaired, exhibited void-free bondlines with no evidence of poor surface wetting. A section through a well repaired delamination showing the typical "hackle" features characteristic of mode II interlaminar fracture can be seen in Figure 16.

6.2 Post-Repair Failure Loads

The mechanical effectiveness of the repairs was investigated by re-loading the HPS specimens and comparing the post-repair failure loads with the initial damage loads. The load-displacement curves, an example of which is shown in Figure 17, were linear to

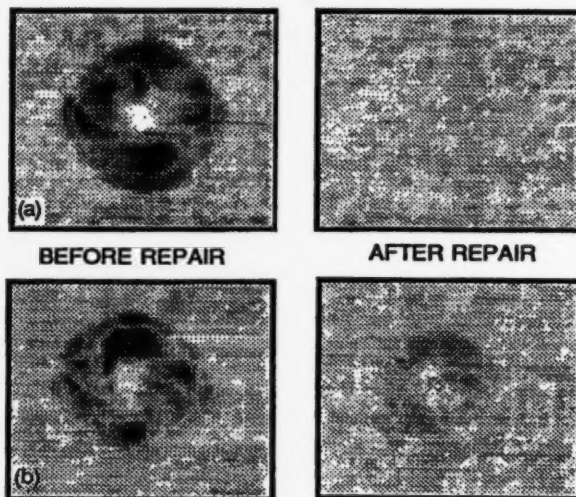


Figure 15. Ultrasonic C-scan images taken before and after repair.

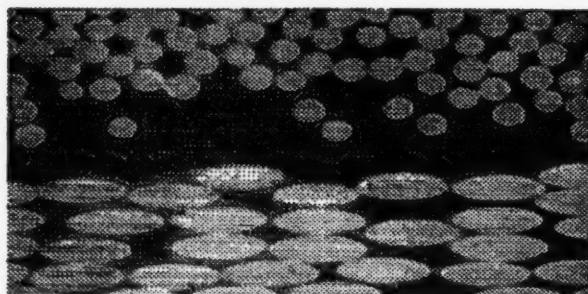


Figure 16. Section through a rebonded delamination.

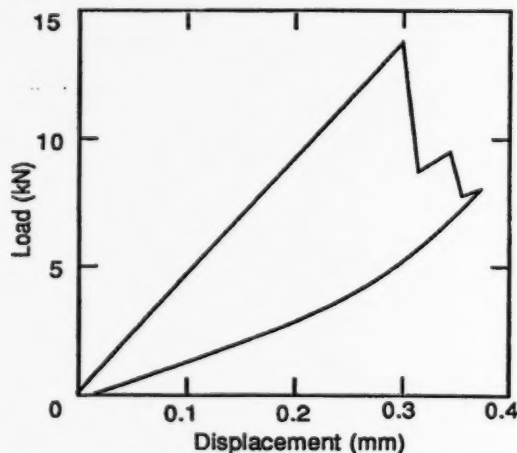


Figure 17. Example of a load-displacement curve for a holed plate shear test.

failure and the maximum load was found to be quite reproducible from specimen to specimen. Preliminary tests revealed that it was necessary to repair the initial hole drilling damage prior to the first loading in order to obtain a valid comparison [5]. Figure 18 shows that at

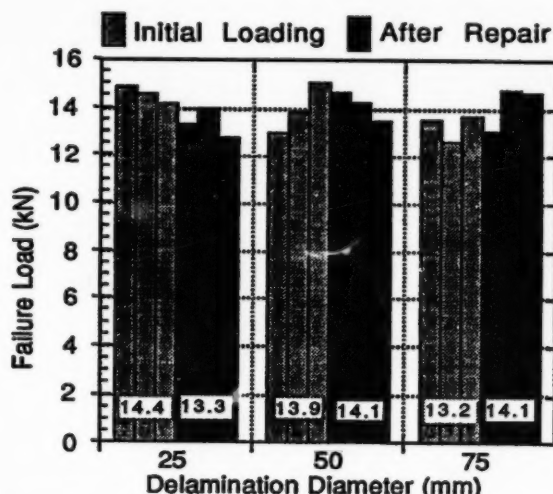


Figure 18. Restoration of HPS failure load as a function of delamination size.

ambient temperature all of the post-repair failure loads were within 10% of the initial values. The loading compliances were also restored but these were found, in general, to be a less sensitive measure of the quality of the repair. At elevated temperatures, Figure 19, the effectiveness of the repairs gradually decreases reflecting the lower T_g of the DREp resin compared to that of the matrix.

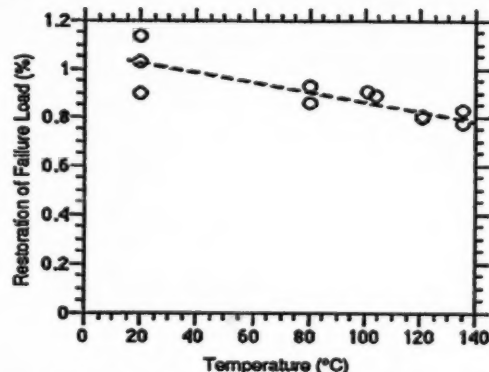


Figure 19. Effect of temperature on the restoration of the HPS specimen failure loads.

7. IMPACT DAMAGE REPAIR

7.1 Restoration of Compression Strength

A series of tests were carried out to assess the effectiveness of resin injection repairs at restoring the compression strength after impact (CAI). Quasi-isotropic laminates of AS4/3501-6 carbon/epoxy, 40 plies thick, were machined into 100 mm x 150 mm CAI specimens. Low velocity impacts of approximately, 10, 20, 30, 40 and 55 joules produced a range of delaminations sizes as shown in Figure 20. At the three lower energies back-surface damage was either absent

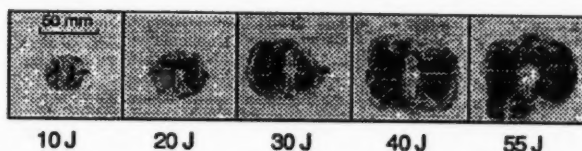


Figure 20. Representative C-scan images of the CAI specimens for each impact energy.

or limited to longitudinal splitting of the outer ply. However, at 40 and 55 joules damage was clearly visible with up to 6 plies protruding beyond the back surface directly beneath the point-of-impact. For each impact energy, 2 specimens were loaded in compression as damaged while 2 were first repaired with the DREp resin. The repair procedure was essentially the same as that described for the HPS specimens except that the resin was forced into the delaminations either through the back surface damage or via 3 or 4 small (<1 mm) holes drilled into the laminate. The test results, plotted in Figure 21, indicate that almost all of the compression strength can be restored for impact energies below 30J and that even when back surface damage is present, acceptable failure strains can still be attained.

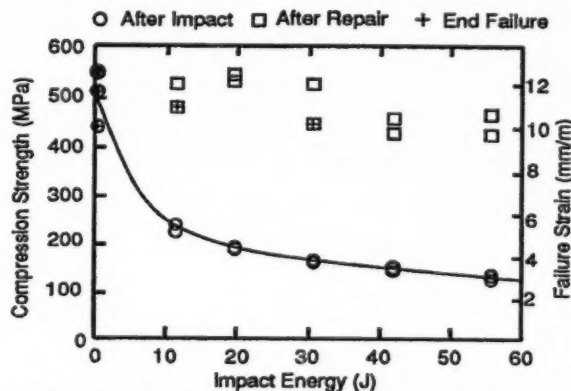


Figure 21. Restoration of compression after impact strength.

7.2 Restoration of Damage Tolerance

A second set of CAI tests were run in order to determine how effective the injection repairs were in restoring the ability of the laminate to sustain further impact damage. As before, 4 plates were impacted at each of five energies; however, only one was tested as damaged, two were repaired and then re-impacted with the same energy as before and one was impacted a second time without repair. Ultrasonic C-scans taken after each impact revealed, Figure 22, that the sizes of the delaminations produced in the repaired plates were significantly smaller than in the as-fabricated specimens. This finding was supported by the compression test data, Figure 23, which indicated that the CAI strengths were greater in the repaired specimens, particularly those impacted at the higher impact energies. Metallographic examination of some of the impacted plates also revealed that the bondline thickness was greater in the plates impacted at the higher energies.

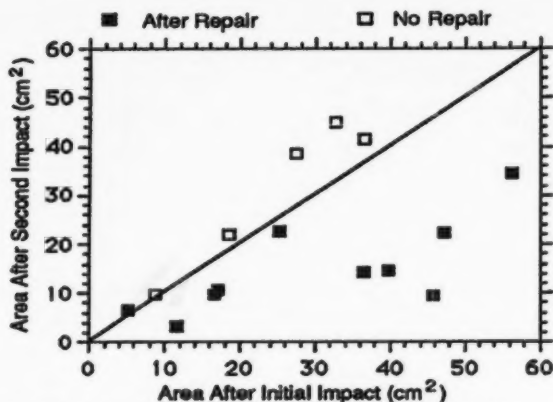


Figure 22. Change in delamination size following second impact.

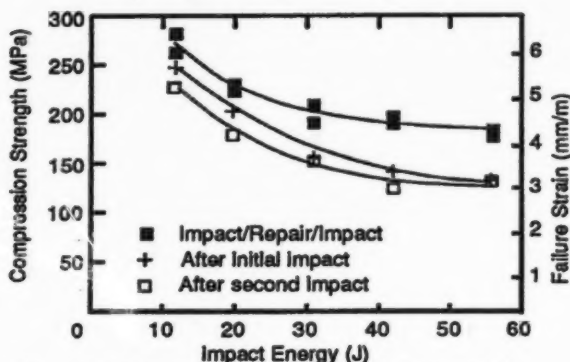


Figure 23. Compression strength after impact of repaired CAI specimens.

8. CONTAMINATION EFFECTS

Unlike most other repair situations involving adhesive bonding, the inaccessibility of the delamination fracture surfaces precludes the use of any normal type of surface preparation prior to resin injection. Consequently, the possibility of one or more of the numerous contaminants, commonly encountered around aircraft, entering into the delaminations prior to repair is of concern. Although, no attempt was made to determine the likelihood of contaminant ingress, some tests were carried out to investigate what effect some typical aircraft fluids might have on the repair strength if they were present inside the delaminations. Five glass beakers, each containing three delaminated HPS specimens were placed in turn in an evacuated chamber and filled with one of the following contaminants; JP-4 jet fuel, H-537 hydraulic fluid, detergent, seawater and "Ultragel" (an ultrasonic couplant). After the specimens were completely covered, the vacuum was vented allowing atmospheric pressure to gradually force the contaminants into the delaminations over a period of 2 months. Upon removal, the specimens were dried for 4 hours at 121°C, repaired as described in section 6.1 and finally reloaded to failure. Ultrasonic C-scans were taken to confirm that the delaminations had been completely infiltrated by the contaminants and also to inspect the repairs.

The test results are shown in Figure 24. The specimens that had been immersed in JP-4 regained most of their initial load bearing capacity, indicating that little or no residue remained after drying. None of the hydraulic

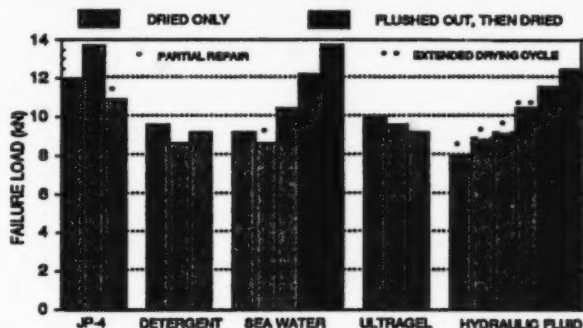


Figure 24. Effect of prior contamination on HPS post-repair failure loads.

fluid contaminated specimens was properly repaired, the C-scans indicating that only the region closest to the fastener hole had been rebonded. Since this suggested that not all of the H-537 had evaporated prior to repair an additional test was run using an extended drying time of 2 days. This specimen did produce a defect-free C-scan but the failure load was still only 80% of the initial value. One further attempt to remove all traces of hydraulic fluid was made by flushing JP-4 through the delaminations of two more specimens, in through the fastener hole and out via 4 small holes drilled around the periphery. This procedure was successful in restoring approximately 90% of the original strength, Figure 24. C-scan images with no defect indications were obtained for all three of the water based fluids but the mean failure loads were all low, between 9.1 and 9.6 kN. In view of the residues left behind when these fluids evaporate as well as the similarities in both the failure loads and loading compliances it is reasonable to assume that these loads represent the maximum attainable by purely mechanical interlocking without any effective adhesion. An attempt was made at removing seawater by flushing distilled water through the delaminations in the same manner as was done with JP-4 for the hydraulic fluid contaminated specimens. The 2 specimens repaired in this manner had failure loads close to the 13kN of the uncontaminated control specimens indicating that most of the seawater had been removed.

9 REPAIR PROCEDURES

9.1 Autoclave repairs

Any components that can be readily removed from the aircraft, can in principle be repaired in an autoclave in a similar manner to the test specimens. Figure 25 illustrates one way that this could be done in practice. Another option would be to limit heating to the repair area alone by means of a heating blanket and to use the autoclave solely for the application of pressure.

9.2 On-Aircraft repairs

For fixed components such as the wing skins of the CF-18 where removal is both time consuming and expensive it is preferable to repair delaminations and impact damage on the aircraft. However, with access limited to only one side of each skin, it is no longer possible to assume that a vacuum can be maintained

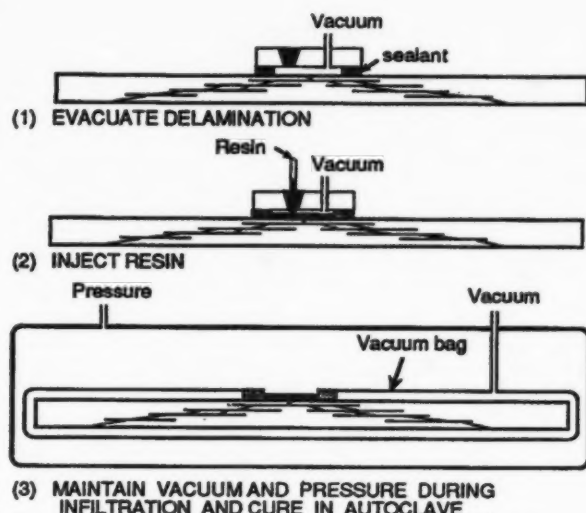


Figure 25. Autoclave delamination repair procedure.

ahead of the advancing resin front. Consequently, it would seem likely that pockets of air would be trapped within the delaminations both as porosity in the bondline as well as in the form of larger unwetted areas. In order to investigate this further 3 HPS specimens were repaired without vacuum by a flow-through procedure in which the resin was forced in through the fastener hole and air allowed to escape via 4 equispaced holes drilled into the periphery of the delaminations. A "resin dam" was taped over each hole to prevent excess loss of resin and to reduce the pressure gradient within the delamination cavity. Rather surprisingly these repairs were just as successful as those carried out using a vacuum, there being no C-scan indications, no bondline porosity and similar post-repair failure loads [6].

One possible arrangement for carrying out this type of on-aircraft flow-through repair is shown in Figure 26.

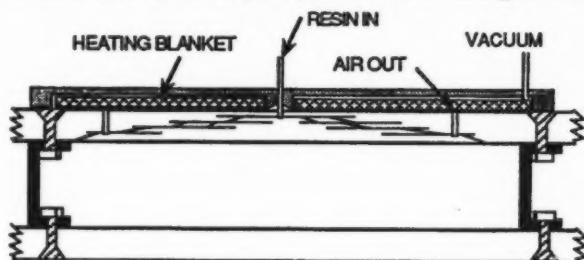


Figure 26. Arrangement for on-aircraft delamination repair.

Here, the vacuum, which is used only to clamp the injection point and heating blanket to the skin, is isolated from the vent holes. Injection pressures in excess of 350 kPa (50 psi) have been consistently achieved with a prototype device of this sort. The major limitation to repairing delaminations in this manner is the presence of sufficient back-surface damage that the resin leaks through the laminate rather than entering the delaminations.

10. CONCLUDING REMARKS

This investigation has clearly demonstrated that when complete infiltration is achieved, resin injection repairs can fully restore the structural integrity of delaminated carbon/epoxy components. Our findings reveal that small delaminations and particularly those in thick laminates are more difficult to infiltrate and have lower than optimum bondline thicknesses. Fortunately, these types of delaminations are much less likely to lead to compression failures and in many instances may not need to be repaired at all. Our results also indicate that repaired delaminations can sustain the same interlaminar shear loadings as the original laminate. This should make it possible to extend delamination repair zones to include locations adjacent to splice plates, ply drop-offs or other sources of interlaminar shear stresses.

Based on our experience, ultrasonic C-scanning, in which the amplitude of any reflections originating from between the front and back surfaces is recorded, should provide an acceptable means of verifying the quality of a repair. Time-of-flight C-scans are useful for determining delamination depths prior to repair but are of limited value in assessing the degree of resin infiltration. For critical repairs where it is suspected that contaminants are present it may also be necessary to flush a suitable solvent through the delaminations and carry out a chemical analysis of the effluent.

From a mechanistic viewpoint, it may appear somewhat surprising that some of the out-of-plane mechanical properties improve following repair since the original chemically cross-linked ply interfaces have been replaced with bonded interfaces relying on adhesion and mechanical interlocking for strength. Evidently, any loss in strength is more than compensated for by the reduction in interlaminar stresses which results from the increased separation of the plies and by the improvement in mode II interlaminar fracture toughness. This is particularly true as the bondline thickness increases i.e. in the larger diameter HPS specimens and in the CAI specimens impacted at the higher energies. In a sense, injection repairs can be regarded as being analogous to interleaved composites where the addition of a layer of toughened epoxy between the plies has been proven to substantially improve the damage tolerance [10].

This investigation into the reparability of delaminations by resin injection was carried out in response to a specific requirement, i.e. the need to be able to repair CF-18 wing skin delaminations caused by either fit-up stresses or by impact damage. Thus, while much of this work may be applicable to other material systems and loading conditions, different circumstances may make it necessary to address other concerns. For example, not only would delaminations grown under predominantly mode I conditions have smoother fracture surfaces but the effectiveness of mechanical interlocking at supporting opening stresses is likely to be considerably less than in shear. Under these conditions, repair validation tests dominated by opening mode stresses would be more appropriate. Also, in instances where delaminations have a tendency to recur, such as at a free edge, it would be preferable if the resistance to delamination could be substantially improved rather than merely restored. While this could probably be achieved by adding a rubber toughening additive to the adhesive, the benefits of this would have to be weighed against the loss in resin flow. On the other hand, for delaminations that are only a few plies

deep, resin flow will be less important but it may be necessary to reduce the injection pressure and devise a means of clamping down the surface plies during infiltration and cure.

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